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Heat and Moisture Production of Poultry and Their Housing Systems: Pullets and Layers

H. Justin Chepete
Iowa State University

Hongwei Xin
Iowa State University, hxin@iastate.edu

Manuel C. Puma
Iowa State University

Richard S. Gates
University of Kentucky

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H. Justin Chepete, Ph.D.

Hongwei Xin, Ph.D.
Member ASHRAE

Manuel C. Puma, Ph.D.

Richard S. Gates, Ph.D.
Member ASHRAE

ABSTRACT

Heat and moisture production rates (HP, MP) of modern pullets and laying hens were measured using large-scale indirect calorimeters that mimic commercial production settings. The experimental birds were Hy-Line W-36 strain at 1-5, 10, 21, 37, and 64 weeks of age and Hy-Line W-98 strain at 1-5 weeks of age. Total HP (THP) was partitioned into latent and sensible HP (LHP, SHP) at bird level (excluding moisture evaporation from feces) or room level (including fecal moisture evaporation from feces). The W-98 and W-36 pullets reached their metabolic peak at about 10 and 14 days of age, respectively. The W-98 pullet showed higher THP than the W-36 counterpart. Modern pullets have significantly higher THP (12% to 37%; $P < 0.05$) than pullets of 20 to 50 years ago. At the initial stage of egg production, the W-36 layers showed 12% higher THP than that predicted by the CIGR (1999) model, and the difference diminished with time. Evaporation of fecal moisture elevated room LHP by 8% to 38% (average 14%) during light period and by 21% to 79% (average 43%) during dark period but reduced room SHP by 4% to 17% (average 11%) during light period and by 14% to 33% (average 22%) during dark period with reference to bird LHP or SHP. All HP responses in the dark were significantly ($P<0.05$) reduced to various degrees (e.g., 23% to 34% for THP) as compared with those during light period. Diurnal bird and room LHP amounted to, respectively, 17% to 87% (average 47%) and 33% to 99% (average 62%) of THP for pullets and, respectively, 29% to 50% (average 39%) and 29% to 55% (average 45%) of THP for laying hens. Respiratory quotient (RQ) ranged from 0.77 to 1.18 (average 0.94) for pullets and from 0.68 to 1.02 (average 0.91) for laying hens. Regression functions that relate daily mean THP, LHP, and SHP of the bird or room to bird body mass were established. Results of this study provide an updated thermal load database for design and operation of poultry housing ventilation systems, as well as the latest bioenergetics of modern pullets and hens.

INTRODUCTION

Heat and moisture production rates (HP, MP) of animals and their surroundings are the basis for efficient design and operation of environmental control systems of production facilities. The magnitude of HP and MP is subject to influence of animal genetics, nutrition, housing type, production equipment, and management practices, all of which have witnessed significant advancements over the years (Reece and Lott 1982a, 1982b; Gates et al. 1996; Xin et al. 1998). For instance, Havenstein et al. (1991) reported a 350% increase in growth rate of modern broiler chickens compared with those in 1957. Sensible HP (SHP) and MP of a litter floor-type broiler house was found by Reece and Lott (1982a) to be, respectively, much lower and higher than SHP and MP of the bird reported from earlier calorimetric studies in the literature (Longhouse et al. 1960). Light or darkness has been shown to have significant impact on HP and MP of poultry (Riskowski et al. 1977; Zulovich et al. 1987; Xin et al. 1996).

An extensive literature review of HP and MP of poultry (pullets, layers, broilers, and turkeys) and their housing systems recently performed by Chepete and Xin (2002) revealed that most HP and MP data in the literature are 20 to 50 years old, and that considerable gaps exist in the data for certain species or production stages. For example, the only HP and MP data documented for pullets covered the growth period of 1 to 7 weeks of age (Zulovich et al. 1987), and there were no data for pullets and layers between 7 and 33 weeks of

H. Justin Chepete is a former graduate research assistant, **Hongwei Xin** is a professor, and **Manuel C. Puma** is a former post-doctoral research associate in the Agricultural and Biosystems Engineering Department, Iowa Sate University, Ames, Iowa. **Richard S. Gates** is a professor and chair in the Biosystems and Agricultural Engineering Department, University of Kentucky, Lexington, Ky.

age. The result further confirmed the need to systematically update HP and MP characteristics of modern poultry for design and operation of environment-controlled poultry housing, as had been suggested by Gates et al. (1996), Xin et al. (1998), and ASHRAE (2001).

This study was a part of the effort toward accomplishing the aforementioned need. The specific objectives of this study were (1) to measure HP and MP of pullets and layers using large-scale indirect calorimeters that mimic commercial production settings with respect to thermal environment, stocking density, feeding and water scheme, photoperiod, and manure handling practices; (2) to compare the results with those currently available in the literature; (3) to evaluate the contribution of fecal and surrounding moisture sources to room MP by separately quantifying latent HP (LHP) of bird vs. room; and (4) to establish functional relationships between HP or MP and bird body mass.

MATERIALS AND METHODS

Experimental Facility and Bird Handling

An indirect calorimeter system, consisting of four calorimeter chambers (1.5 [W] × 1.8 [D] × 2.4 [H] m) (Xin and Harmon 1996; Xin et al. 1998), was used for this study (Figure 1). In particular, the gas (O_2 and CO_2) analyzers were calibrated daily throughout the experimental periods to ensure an HP measurement system uncertainty of ±0.5 watt per chamber (>65 watt HP output per chamber). In each trial performed for both pullets and layers, two randomly selected chambers had oil pans placed under the cages to submerge the feces, thereby preventing interference of fecal moisture evaporation with measurement of HP and MP from birds only. The other two calorimeters had no oil in the catching pans (as would be the case with manure belt), and, thus, MP included contribution from both birds and feces. Manure was removed from all chambers twice weekly, after which oil was replenished to ensure complete submergence of feces. Birds were group-weighed weekly throughout the trials, so that regression models could be established and used for calculation of specific HP and MP.

Bird mortality was continuously monitored and excluded from calculation of total body mass for determination of specific HP and MP. The commercially practiced management schemes (feeding, lighting program, temperature, stocking density, and manure handling) were followed throughout all the trials, as described below. At the end of each trial, the calorimeter chamber system was cleaned, disinfected, maintained (as needed), and unoccupied for a week or longer before the next trial.

Measurements of HP and MP

Pullets. Two separate groups of Hy-Line W-36 and W-98 pullets were measured for the pullet study, each covering a zero- to five-week growth period. Each group consisted of 720 chicks. Upon delivery from the commercial hatchery to the measurement laboratory, the chicks were group-weighed and

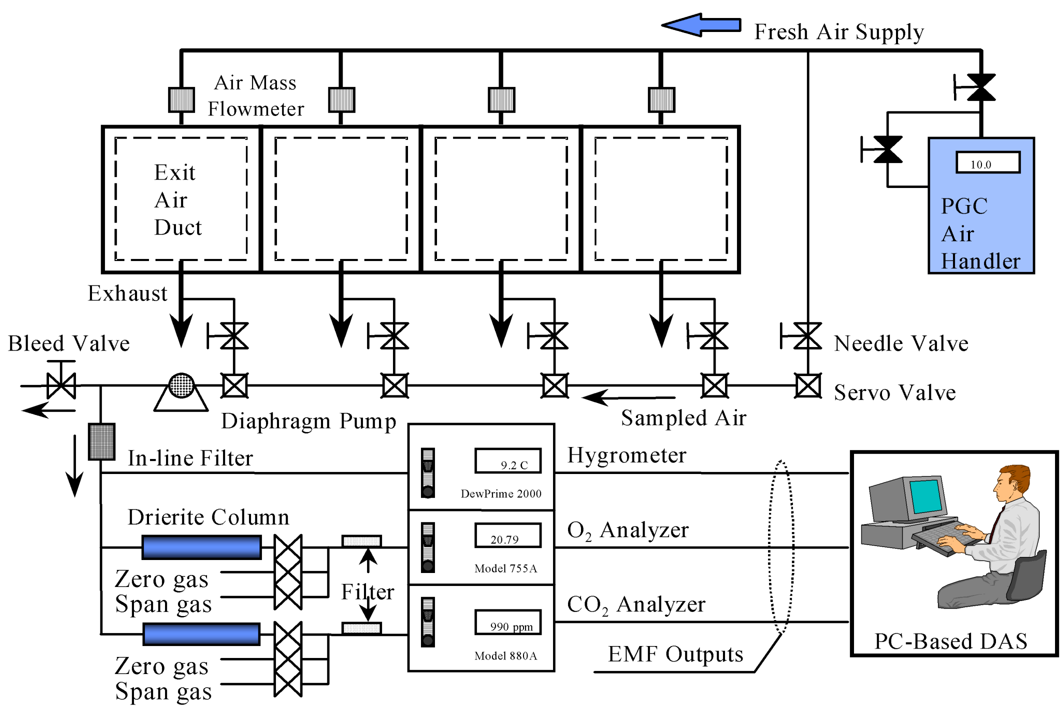

Figure 1 *A schematic representation of the indirect calorimeter system used in the present study.*

randomly allocated to the four indirect calorimeter chambers. Each chamber had a movable supporting stand with nine cages (55 [L] ×50 [W] × 41 [H] cm each). Twenty-day-old chicks were initially allocated to each cage and were thinned down to 15 and 10 at the start of weeks 3 and 4, respectively, which led to 180, 135, and 90 birds per chamber, respectively. These bird numbers ensured sufficient changes in air composition (O_2 and CO_2) of the calorimeter chambers for the instruments to make accurate measurements.

Thermoneutral (TN) air temperature was maintained in all chambers during the growth and measurement period. Specifically, air temperature inside the calorimeters was kept at 32°C during the first two days and was reduced by 1°C every three days thereafter until 21°C, where it remained constant. The corresponding relative humidity (RH) ranged from 35% to 50% throughout the trial. The chicks were provided continuous lighting for the first two days, then 15hL:9hD until two weeks of age and, thereafter, 12hL:12hD until the end of the trial at five weeks of age. Light intensity was 16-21 lux for the first two days and 5-11 lux for the remainder of the trial. Free access to feed and water through nipple drinkers was provided. A prestarter ration was fed for the first week, followed by a starter ration (Table 1).

To bridge gaps in the literature data, HP and MP of W-36 pullets at ten weeks of age were measured, involving a total of 324 birds. The pullets were group-weighed and randomly allocated to the calorimeters with 81 birds per chamber (9 birds per cage). The measurement lasted for four weeks. The room temperature was 22°C during the first week, 28°C during the second and part of the third week, and back to 22°C during part of the third and the fourth week. Light intensity was 5-11 lux throughout the trial period. RH varied from 35% to 50% the entire time. Photoperiod was 12hL:12hD. The birds had free access to feed (Table 1) and nipple drinkers.

Laying hens. HP and MP of W-36 laying hens were measured for 21, 37, and 64 weeks of age to reflect various production stages of the hens. Each age group was studied over a three-week period. The temperature regimen was 24°C (TN), 30°C (warm), and back to 24°C during the first, second, and third week, respectively. Only data associated with the first week are presented in this paper. Each age group involved a total of 252 hens procured from local commercial farms. The hens were randomly allocated to the calorimeter chambers, 63 birds per chamber, 7 hens per cage. RH ranged from 35% to 50% for the entire measurement period. Light scheme of 13hL:11hD, 16hL:8hD, and 16hL:8hD at an intensity of 5-11 lux was used, respectively, for 21-, 37- and 63-week old hens. Eggs were collected twice daily to minimize breakage that would otherwise interfere with MP measurement. Free access to feed (Table 1) and water through nipple drinkers was provided.

Data Analysis and Presentation

For each 24-h period of the trials, data were separated into dark and light periods and their time-weighted averages (TWA) determined. Total HP (THP) was further partitioned into latent HP (LHP) and SHP of bird or room, as described above. The data were subjected to analysis of variance using statistical analysis software. Regression models were developed to relate the HP responses to body mass (M) of the bird.

Table 1. Dietary Ingredients (%, Unless Otherwise Noted) of Feed Used in the Study

	W-36 and W-98 Pullets (0-35 d)		W-36 Birds			
Dietary Content	Prestarter Ration	Starter Ration	10 wk	21 wk	37 wk	64 wk
ME (MJ/kg)	12.20	12.20	12.70	11.80	11.60	12.20
Crude protein	21.00	20.20	16.50	18.00	14.82	15.80
Crude fat	3.10	3.30	3.60	N/A	2.77	N/A
Crude fiber	3.50	4.10	3.80	N/A	2.37	N/A
Calcium	1.04	1.04	1.04	4.25	4.42	4.12
Total phosphorus	0.75	0.65	0.66	0.76	0.47	N/A
Available phosphorus	0.52	0.43	0.47	0.57	N/A	0.31
Sodium	0.18	0.18	0.16	0.21	0.21	0.18
Total Iysine	1.19	1.11	0.83	N/A	0.80	N/A
Lysine	N/A	N/A	N/A	1.03	N/A	0.82
Methionine	N/A	N/A	N/A	0.51	N/A	0.36
Total methionine	0.50	0.48	0.39	N/A	N/A	N/A
Methionine and Cystine	0.86	0.82	0.69	N/A	0.61	N/A
Choline (mg/lb)	N/A	N/A	N/A	N/A	N/A	518.50

N/A = Information not available

The HP and MP data of pullets during the first two days inside the calorimeter chamber and the first day for the 10- to 64-week old birds were excluded in the development of the models as the birds were acclimating to the new environment. Data collected during cleaning and weighing of the birds were also excluded from analysis.

RESULTS AND DISCUSSION

Body mass (M [kg]) and age (D [day]) of the birds had the following functional relationships:

For W-98 pullets ($3 \le D \le 35$),

$$M = 1.46 \times 10^{-4} D^2 + 3.71 \times 10^{-3} D + 0.0295 \quad (R^2 = 1.000) \tag{1}$$

For W-36 birds ($3 \le D \le 70$),

$$M = -3.00 \times 10^{-6} D^3 + 0.0004D^2 - 0.0004D + 0.0463 \quad (R^2 = 0.999) \tag{2}$$

For W-36 birds ($70 \le D \le 448$),

$$M = 9 \times 10^{-8} D^3 - 8 \times 10^{-5} D^2 + 0.0218D - 0.3533 \quad (R^2 = 1.000) \tag{3}$$

These relationships are shown in the graphs of THP, LHP, and SHP as a function of M.

The THP, LHP, SHP, and respiratory quotient (RQ, CO_2/O_2) at bird and room levels (LHP and SHP) for light, dark, and TWA conditions at various growth and production stages are summarized in Table 2. There was no significant difference in THP between the calorimeters with or without oil pans ($P > 0.52$). Thus, THP values from all four calorimeters were pooled in the analysis.

The THP regression models developed had the form of THP = aM^b and are presented in Table 3. Selection of the THP model form was based on the physiological phenomenon that metabolic rate is directly proportional to M raised to a certain power or metabolic mass unit (Brody 1945). The regression models for LHP and SHP were quadratic polynomials in the form of LHP or SHP (W/kg) = $aM^2 + bM + c$ and are presented as bird or room values in Tables 4 and 5, respectively. Although THP remains unchanged under a given TN condition, the partitioning of THP into SHP and LHP can be greatly influenced by the contribution of ambient moisture and heat sources. This explains the use of polynomial equations to describe the relationships between the SHP or LHP and bird body mass. The numerical differences in LHP or SHP between the table values and those derived from regression models were inevitable. For design purposes, use of the table values (e.g., Table 2) is recommended, whenever possible.

The contribution of feces and other surrounding elements to the elevation of room LHP and reduction of room SHP can be noted for various growth and production stages in Figures 2 and 3. While bird LHP and SHP provide insights into delineation of thermoregulation, room LHP and SHP provide a more realistic basis for design and operation of the housing ventilation system.

Metabolic Peak Period

During the initial stage of growth, specific THP of the pullets increased progressively and reached its peak at a certain age (Figure 2 for W-98 and Figure 3 for W-36). This period is known as the “metabolic peak period” (Brody 1945). The W-98 pullet reached the metabolic peak (17.8 W/kg) at about ten days of age, while the W-36 counterpart reached the peak (15.4 W/kg) at about 14 days of age (Table 2). This result parallels a report from the industry that the W-98 strain reaches maturity at an earlier age than the W-36 strain. Specifically, W-98 birds begin egg production at 16 to 17 weeks of age, as compared with 18 to 19 weeks for W-36 hens (Hy-Line 2000-2001). During this peak period, THP of the W-98 pullet ranged from 16.0 to 17.8 W/kg, as compared with THP of 12.8 to 15.4 W/kg for the W-36 pullet. Figure 3 shows a somewhat higher metabolic peak for the W-36 pullet. This resulted from a curve-fitting artifact while making the two curves meet. However, for W-98 pullets (Figure 2), the two curves fit well.

The LHP steadily increased to a maximum by six days of age for both W-98 and W-36 pullets and then declined, while SHP increased sharply for both species prior to the metabolic peak. This may have resulted from increased metabolic rate as the pullets physiologically develop. SHP of the W-98 pullets continued to rise slightly after metabolic peak while W-36 declined (Figures 2 and 3). This may have contributed to the higher overall THP for the W-98 pullet. The LHP curves were not fitted during this period (Figures 2 and 3) and may be obtained from difference between THP and SHP.

Post-Metabolic Peak Period

THP (W-98 pullet, 10 to 35 d). The TWA THP of the W-98 pullet during a 10- to 35-d growth period ranged from 12.2 W/kg (0.33 kg) to 17.8 W/kg (0.07 kg) (Table 2). In comparison, THP of the pullets calculated from the CIGR (1999) equation of THP (W/kg) = $6.28M^{-0.24}$ was 8.2 and 11.9 W/kg, respectively. The difference amounts to 49%, with CIGR value as the base. When compared with data reported by Zulovich et al. (1987) for Dekalb XL pullet at 14 to 35 d of age (0.11 to 0.33 kg), the W-98 pullet showed 30% to 48% higher THP. During the same period, THP was reduced by 21% to 36% ($P<0.05$) when switching from light to darkness. In comparison, the reduction in THP in darkness for Dekalb XL pullets derived from the study by Zulovich et al. (1987) was 39% to 54% during 14- to 35-d growth period.

THP (W-36 pullet and laying hens, 14 to 448 d). Comparison of the new model of THP [W/bird] = $7.64M^{0.65}$ from this study (Table 3) with the model established by Chepete and Xin (2002) of THP [W/bird] = $6.47M^{0.77}$ based on HP data from 1953 to 1990 (Figure 4) revealed higher THP for

Table 2a. Heat Production Rates and Respiratory Quotient (RQ) of Birds and Housing Room for W-36 Pullets and Layers Fed Ad-Lib and Watered from Nipple Drinkers During Daily Light, Dark, and Time-Weighted Average (TWA) Periods

Age	M	T_a	LHP (W/kg)						SHP (W/kg)						THP (W/kg)			RQ (CO_2/O_2)		
			Light		Dark		TWA		Light		Dark		TWA		Light	Dark	TWA	Light	Dark	TWA
(d or wk)	(kg)	(°C)	Bird	Room	Bird	Room	Bird	Room	Bird	Room	Bird	Room	Bird	Room						
1 d	0.04	32.2	5.8	5.9	*	*	5.8	5.9	1.6	1.5	*	*	1.6	1.5	7.3	*	7.3	1.01	*	1.01
2 d	0.04	32.2	6.1	6.8	*	*	6.1	6.8	4.6	3.9	*	*	4.6	3.9	10.7	*	10.7	1.00	*	1.00
4 d	0.06	31.1	8.2	10.0	5.5	7.2	7.2	8.9	6.0	4.2	5.2	3.5	5.7	4.0	14.2	10.7	12.9	0.95	0.96	0.95
6 d	0.06	31.1	10.3	11.1	5.3	7.7	8.4	9.8	5.9	5.1	6.2	3.9	6.0	4.6	16.2	11.5	14.4	1.03	0.97	1.01
8 d	0.07	30.0	8.4	10.6	5.0	8.0	6.9	9.5	8.7	6.6	6.2	3.2	8.3	5.8	17.2	11.2	15.2	1.05	0.96	1.02
10 d	0.07	28.9	7.8	9.7	4.1	7.2	6.4	8.8	9.6	7.7	7.3	4.2	8.8	6.4	17.4	11.4	15.2	1.00	0.97	0.96
14 d	0.09	27.8	8.5	9.2	4.9	6.5	7.0	8.1	9.2	8.4	7.4	5.7	8.4	7.4	17.6	12.2	15.4	0.96	0.91	0.94
21 d	0.18	25.6	6.9	8.1	5.1	6.8	6.0	7.4	9.9	8.7	6.3	4.6	8.1	6.6	16.7	11.4	14.1	0.95	0.90	0.93
28 d	0.27	22.8	5.1	6.7	2.9	5.2	4.0	6.0	9.8	8.1	6.9	4.6	8.3	6.4	14.9	9.8	12.3	0.97	0.89	0.93
35 d	0.35	21.1	4.7	5.7	2.8	4.1	3.7	4.9	7.7	6.7	5.6	4.3	6.6	5.5	12.4	8.4	10.4	0.99	0.99	0.99
10 wk	0.81	21.1	2.4	3.3	1.7	2.5	2.1	2.9	7.0	6.2	4.7	3.9	5.9	5.1	9.4	6.4	7.9	0.97	0.90	0.94
21 wk	1.40	24.4	2.8	3.0	1.9	2.3	2.4	2.7	4.6	4.4	3.7	3.2	4.2	3.9	7.4	5.6	6.5	0.85	0.90	0.88
37 wk	1.48	24.4	3.2	3.6	2.1	2.8	2.8	3.3	4.6	4.1	3.4	2.7	4.2	3.7	7.8	5.5	7.0	0.95	0.99	0.96
64 wk	1.53	24.4	3.0	3.3	1.9	2.8	2.8	3.1	4.4	4.0	3.7	2.7	4.0	3.6	7.3	5.6	6.7	0.87	0.89	0.88

M = body mass, kg; T_a = ambient temperature, °C; LHP = latent heat production; SHP = sensible heat production; THP = total heat production; THP = $LHP_{bird} + SHP_{bird} = LHP_{room} + SHP_{room}$; LHP_{bird} or SHP_{bird} = values obtained in chambers where oil was used to submerge feces.
LHP room or SHP room = values obtained in chambers where oil was not used to submerge feces.
* = birds subjected to continuous lighting during the first two days
The number of birds per trial was 720 (2-10 d), 540 (14-21 d), 360 (28-35 d), 324 (10 wk), or 252 (21-64 wk).
Relative humidity ranged from 35% to 50%.
Duration of trials was 5 wk continuously for 2- to 35-day-old pullets or 7 d continuously for 10- to 64-week-old birds.

Table 2b. Heat Production Rates and Respiratory Quotient (RQ) of Birds and Housing Room for W-98 Pullets Fed Ad-Lib and Watered from Nipple Drinkers During Daily Light, Dark, and Time-Weighted Average (TWA) Periods

Age	*M*	T_a	LHP (W/kg)						SHP (W/kg)						THP (W/kg)			RQ (CO_2/O_2)		
			Light		Dark		TWA		Light		Dark		TWA		Light	Dark	TWA	Light	Dark	TWA
(d or wk)	(kg)	(°C)	Bird	Room	Bird	Room	Bird	Room	Bird	Room	Bird	Room	Bird	Room						
1 d	0.03	32.2	8.6	12.9	*	*	8.6	12.9	1.8	–2.4	*	*	1.8	–2.4	10.4	*	10.4	0.93	*	0.93
2 d	0.04	32.2	9.0	11.2	*	*	9.0	11.2	3.6	1.5	*	*	3.6	1.5	12.6	*	12.6	0.93	*	0.93
4 d	0.06	31.1	13.7	15.1	7.1	11.1	11.2	13.6	4.7	3.3	6.0	2.0	5.2	2.8	18.4	13.1	16.4	0.94	0.9	0.93
6 d	0.06	31.1	14.4	15.3	8.2	11.7	12.1	14.0	4.7	3.8	6.4	2.8	5.3	3.4	19.1	14.5	17.4	0.91	0.89	0.90
8 d	0.07	30.0	12.7	14.0	6.7	10.4	10.5	12.7	6.2	4.9	8.1	4.4	6.9	4.7	18.9	14.8	17.4	0.87	0.9	0.88
10 d	0.07	28.9	10.7	12.0	6.4	9.1	9.1	10.9	8.7	7.4	8.9	6.2	8.7	6.9	19.4	15.3	17.8	0.90	0.91	0.91
14 d	0.09	27.8	8.7	9.4	5.5	7.5	7.4	8.6	8.9	8.1	7.6	5.6	8.3	7.1	17.5	13.1	15.7	0.95	1.0	0.95
21 d	0.17	25.6	7.1	8.7	3.6	5.8	5.4	7.3	10.9	9.3	7.9	5.7	9.4	7.5	78.0	11.5	14.8	0.95	0.91	0.93
28 d	0.25	22.8	6.0	7.1	3.2	4.9	4.6	6.0	9.4	8.3	7.4	5.6	8.4	7.0	15.4	10.6	13.0	0.98	0.9	0.93
35 d	0.33	21.1	4.9	5.5	2.5	3.9	3.7	4.7	9.8	9.2	7.3	5.9	8.5	7.6	14.7	9.8	12.2	0.98	0.92	0.95

M = body mass, kg; T_a = ambient temperature, °C; LHP = latent heat production; SHP = sensible heat production; THP = total heat production; THP = $LHP_{bird} + SHP_{bird} = LHP_{room} + SHP_{room}$; LHP_{bird} or SHP_{bird} = values obtained in chambers where oil was used to submerge feces.
LHP room or SHP room = values obtained in chambers where oil was not used to submerge feces.
* = birds subjected to continuous lighting during the first two days
The number of birds per trial was 720 (2-10 d), 540 (14-21 d), 360 (28-35 d), 324 (10 wk), or 252 (21-64 wk).
Relative humidity ranged from 35% to 50%.
Duration of trials was 5 wk continuously for 2- to 35-day-old pullets or 7 d continuously for 10- to 64-week-old birds.

Table 3. Regression Models of Time-Weighted Average Total Heat Production Rate (THP, W/kg or W/bird) vs. Body Mass (M, kg) for W-98 and W-36 Birds: THP (W/kg) = aM^b or THP (W/bird) = aM^c (where $c = 1 + b$)

Variable	W-98	W-36
	3-10 d (0.04-0.07 kg, R^2 = 0.25)	3-14 d (0.04-0.09 kg, R^2 = 0.59)
a	26.98 (4.07)	27.86 (2.43)
b	0.16 (0.05)	0.25 (0.03)
c	1.16	1.25
	10-35 d (0.07-0.33 kg, R^2 = 0.76)	14-448 d (0.09-1.53 kg, R^2 = 0.95)
a	9.34 (0.24)	7.64 (0.07)
b	–0.24 (0.01)	–0.35 (0.01)
c	0.76	0.65

Values in parentheses are standard errors.

Table 4. Regression Models for Time-Weighted Average Latent Heat Production Rate (LHP, W/kg) vs. Body Mass (M, kg) for W-98 and W-36 Birds: LHP = $aM^2 + bM + c$

Variable	W-98 Pullet		W-36 Pullet and Layers	
	Bird LHP	Room LHP	Bird LHP	Room LHP
	10-35 d (0.07-0.33 kg)		14-448 d (0.09-1.53 kg)	
	R^2 = 0.91	R^2 = 0.88	R^2 = 0.88	R^2 = 0.93
a	79.28 (12.41)	47.93 (15.09)	5.88 (0.37)	5.73 (0.33)
b	–50.85 (5.16)	–39.54 (6.34)	–11.85 (0.63)	–12.34 (0.57)
c	12.05 (0.48)	12.77 (0.60)	7.42 (0.17)	8.88 (0.16)

Values in parentheses are standard errors.

Table 5. Regression Models of Time-Weighted Average Sensible Heat Production Rate (SHP, W/kg) vs. Body Mass (M, kg) for W-98 and W-36 Birds: SHP = $aM^2 + bM + c$

Variable	W-98 Pullet		W-36 Pullet and Layers	
	Bird SHP	Room SHP	Bird SHP	Room SHP
	3-10 d (0.04-0.07 kg)		3-14 d (0.04-0.09 kg)	
	R^2 = 0.58	R^2 = 0.88	R^2 = 0.56	R^2 = 0.85
a	–1209.26 (2105.65)	–1773.13 (1200.68)	–1235.98 (594.93)	–922.45 (425.08)
b	245.20 (260.44)	351.46 (150.58)	239.59 (93.77)	203.00 (665.51)
c	–4.54 (7.8)	–9.89 (4.56)	–3.14 (3.43)	–4.13 (2.33)
	10-35 d (0.07-0.33 kg)		14-448 d (0.09-1.53 kg)	
	R^2 = 0.37	R^2 = 0.02	R^2 = 0.91	R^2 = 0.80
a	–64.63 (16.24)	–13.06 (17.3)		
b	30.40 (6.85)	4.94 (7.37)	–3.57 (0.11)	–2.43 (0.13)
c	4.94 (0.65)	6.95 (0.71)	9.17 (0.12)	7.31 (0.13)

Values in parentheses are standard errors.

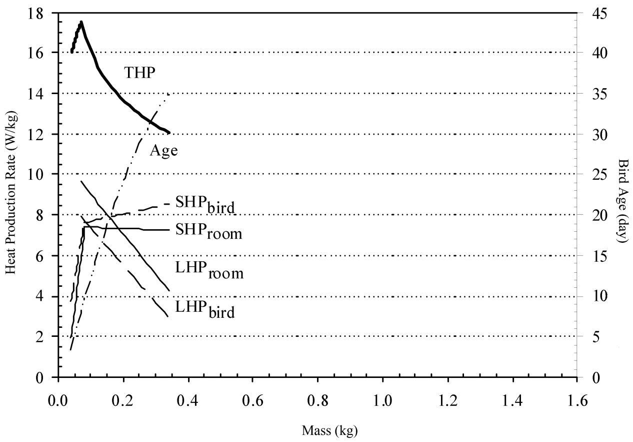

Figure 2 *Specific heat production rate for 3- to 35-d-old W-98 pullet at thermoneutrality (21°C to 32°C) as a function of body mass based on time-weighted average (TWA) best-fit regression models of the measured data in the current study.*

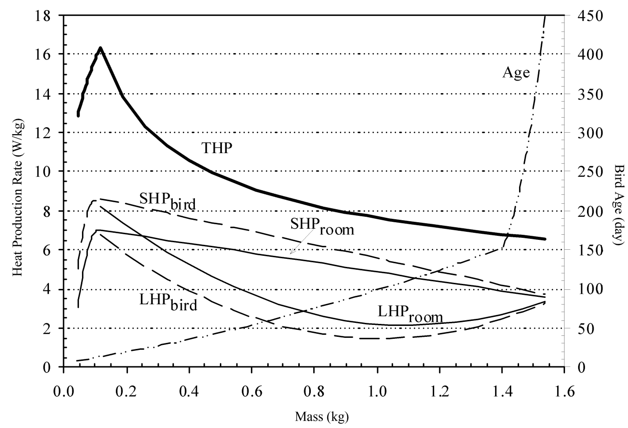

Figure 3 *Specific heat production rate for 3- to 448-d-old W-36 pullet and laying hens at thermoneutrality (21°C-32°C) as a function of body mass based on time-weighted average (TWA) best-fit regression models of the measured data in the current study.*

modern birds. Specifically, THP averaged 0.8 to 6.5 W/kg (12% to 37%) higher for modern pullets of 0.09 to 1.36 kg. The elevated THP of modern birds presumably results from improved genetics and nutrition.

Further comparison was made with the CIGR (1999) model of THP [W/bird] = $6.28M^{0.76} + 25Y$, where Y = egg production, kg/d-hen (Figure 4). Egg production (Y) was derived from the performance data in the *Hy-Line W-36 Commercial Management Guide* (Hyline 2000-2001), having the form of Y [kg/d-hen] = $-36.07M^3 + 156.17M^2 - 224.84M + 107.67$ for M = 1.36 to 1.53 kg (R^2 = 0.997). For pullets of M = 0.09 to 1.36 kg (post-metabolic peak period), Y = 0, the model of this study showed 1.0 to 6.6 W/kg or 15% to 37% higher THP than that predicted by the CIGR model. On the other hand, for laying hens of M = 1.36 to 1.53 kg, the new model was 12% higher at the onset of egg production (1.36 kg), and the difference became negligible with time. The THP curvature of the CIGR model for M = 1.40 to 1.53 kg (Figure 4) was a result of the egg production profile of the hen (i.e., reaches peak and then declines). The slightly higher THP values for the CIGR model during this period could have resulted from use of egg production that was higher than the actual values. Statistical comparisons of the models could not be performed due to differences inherent in the data used in development of each model, which includes time of study, bird genetics, management practices, and feed used.

Daily TWA THP of this study ranged from 6.5 (1.40 kg) to 15.4 (0.09 kg) W/kg and was 23% to 34% lower in the dark than in the light period (Table 2). Li et al. (1991), MacLeod and Jewitt (1984), and Riskowski et al. (1977) reported THP to be, respectively, 33%, 35%, and 22% lower in darkness. The

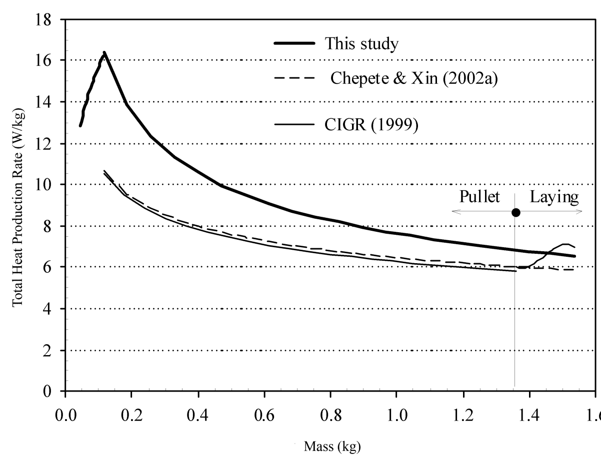

Figure 4 *Comparison of total heat production rate (THP) best-fit regression models of pullet and laying hens at thermoneutrality (21°C-32°C) as a function of body mass.*

greater THP in light period is attributed to bird physical activity (Li et al. 1991; Boshouwers and Nicaise 1985; Feddes et al. 1985; Brody 1945) and posture (Li et al. 1991).

Riskowski et al. (1977) and Feddes et al. (1985), respectively, reported THP of 5.6 W/kg for Hy-Line W-36 laying hens at 1.7 kg and THP of 5.0 W/kg for White Leghorn hens at 1.50 kg. The W-36 hen at 1.53 kg in the current study had an average THP of 6.7 W/kg. Ota and McNally (1961) found

THP of 5.7 W/kg for 1.54 kg (37-week old) White Leghorn hens during light period, as compared with 7.8 W/kg for W-36 hen of the same age (37-week) but slightly lighter *M* (1.48 kg), or 7.3 W/kg for W-36 hen of similar *M* (1.53 kg) in the current study. Changes in bird genetics, nutrition, and productivity level may have contributed to the THP differences. Due to HP data gap in the literature (Chepete and Xin 2002), HP comparison for birds at 10 and 21weeks of age under TN conditions could not be made.

LHP (W-98 pullet). Bird LHP ranged from 4.9 (0.33 kg) to 10.7 (0.07 kg) W/kg during light period and from 2.5 to 6.4 at the same *M* during dark period (Table 2), i.e., 37% to 49% lower in darkness ($P < 0.05$). The corresponding room LHP ranged from 5.5 to 12.0 W/kg during light period and from 3.9 to 9.1 W/kg during dark period. Compared with W-36 pullet at 10- to 35-d of age (table 2), W-98 pullet generally had higher LHP, which was consistent with field observation that W-98 birds tend to consume more water and, thus, have wetter droppings. However, moisture content of the manure was not monitored in the current study. Room LHP was 20% to 33% lower in darkness ($P < 0.05$) as compared with a 9% to 17% reduction reported by Zulovich et al. (1987) for Dekalb XL pullets at 7- to 35-d of age.

With reference to bird LHP, moisture evaporation from feces increased room LHP by 8% to 23% during light period and by 36% to 61% during dark period. Relative contribution of fecal moisture evaporation to room LHP was greater during dark period than during light period, presumably due to reduced bird LHP in the dark (reduced activity), while LHP from the manure remained relatively constant. Xin et al. (2002), May and Lott (1994), and Xin et al. (1993) reported that birds tend to feed and drink more rigorously just before lights off (anticipatory feeding and drinking), which would lead to increased defecation during the subsequent dark period.

LHP (W-36 pullet and laying hens). Bird LHP ranged from 2.4 (0.81 kg) to 8.5 (0.09 kg) W/kg during light period and from 1.7 (0.81 kg) to 5.1 (0.18 kg) W/kg during dark period, i.e., 26% to 42% lower in darkness ($P < 0.05$). In particular, W-36 hens at 37 weeks of age (1.5 kg) showed bird LHP reduction of 34% when switching from light to dark. This value compared well with the reduction of 28% to 31% derived from the study by Ota and McNally (1961) for White Leghorn laying hens of the same age (1.6 kg). TWA bird LHP was 2.8 W/kg for 1.53 kg birds of this study, while Riskowski (1978) reported a value of 1.2 W/kg for 1.7 kg Hy-Line W-36 birds.

Room LHP during this period ranged from 3.0 (1.40 kg) to 9.2 (0.09 kg) W/kg during light period and 2.3 (1.40 kg) to 6.8 (0.18 kg) W/kg during dark period, i.e., 15% to 29% lower in darkness ($P < 0.05$). Moisture evaporation from feces increased room LHP by 8% to 38% (averaging 18%) and 21% to 79% (averaging 43%) during light and dark periods, respectively.

SHP (W-98 pullet). Bird SHP ranged from 8.7 (0.07 kg) to 10.9 (0.17 kg) W/kg during light period and from 7.3 (0.33 kg) to 8.9 (0.07 kg) W/kg during dark period, i.e., 15% to 28% lower in darkness ($P < 0.05$). Room SHP ranged from 7.4 (0.07 kg) to 9.3 (0.17 kg) W/kg during light period and from 5.6 (0.09 kg) to 6.2 (0.07 kg) W/kg during dark period, i.e., 16% to 39% lower ($P < 0.05$). Room SHP derived from data by Zulovich et al. (1987) for Dekalb XL pullets at 14- to 35-d of age (0.11-0.33 kg) was 48% to 71% lower in darkness. Han and Xin (2000) reported a 21% to 27% reduction in THP, room LHP, and SHP for 3-d-old Hy-Line GP male chicks from light to dark. With reference to bird SHP, moisture evaporation from feces reduced room SHP by 6% to 15% (averaging 11%) during light period and by 19% to 30% (averaging 26%) during dark period.

SHP (W-36 pullet and laying hens). Bird SHP ranged from 4.4 (1.53 kg) to 9.9 (0.18 kg) W/kg during light period and 3.4 (1.48 kg) to 7.4 (0.09 kg) W/kg during dark period, i.e., 16% to 36% lower in darkness ($P < 0.05$). A 26% reduction in bird SHP from light to dark was observed with the 37-week-old (1.5 kg) hens of this study. In comparison, data reported by Ota and McNally (1961) for White Leghorn laying hens of the same average age (1.6 kg) revealed a 2% to 10% reduction. TWA bird SHP of this study was 4.0 W/kg for 1.53 kg birds, while Riskowski et al. (1978) reported a value of 4.4 W/kg for 1.7 kg Hy-Line W-36 birds. The room SHP ranged from 4.0 (1.53 kg) to 8.7 (0.18 kg) W/kg during light period and from 2.7 (1.53 kg) to 5.7 (0.09 kg) W/kg during dark period, i.e., 27% to 47% lower in darkness ($P < 0.05$). Moisture evaporation from feces reduced room SHP by 4% to 17% (averaging 11%) during light period, and by 14% to 33% (averaging 22%) during dark period. O'Connor et al. (1997) and Feddes et al. (1985) reported room SHP reduction of 18% to 34% and 4% to 8%, respectively, as a result of SHP conversion into room LHP for 3.6 kg Arbor Acres broiler breeders (O'Connor et al. 1997) and White Leghorn laying hens (Feddes et al. 1985) both raised in commercial barns.

Respiratory Quotient (RQ)

The RQ values at the selected age or *M* levels are presented in Table 2. They varied from 0.89 to 1.05 (averaging 0.94) for 3- to 70-day-old pullets and from 0.85 to 1.05 (averaging 0.91) for 21- to 64-week-old laying hens. Ketelaars et al. (1985) reported an RQ of 0.92 for laying hens at normal production. Ouwerkerk and Pedersen (1994) stated that RQ depends on metabolic rate, feed intake, and individual status of the animal, adding that it increases with feed intake.

Diurnal HP and MP Profiles

Diurnal HP, MP or LHP, and RQ profiles for selected trials are shown in Figures 5 through 10. Bird or room LHP (LHP_{bird}, LHP_{room}) were expressed as a percentage of THP. For pullets at four days and ten weeks of age, LHP_{bird} was 17% to 87% (averaging 47%) of THP, and LHP_{room} was 33% to 99% (averaging 62%) of THP. The instantaneously high LHP

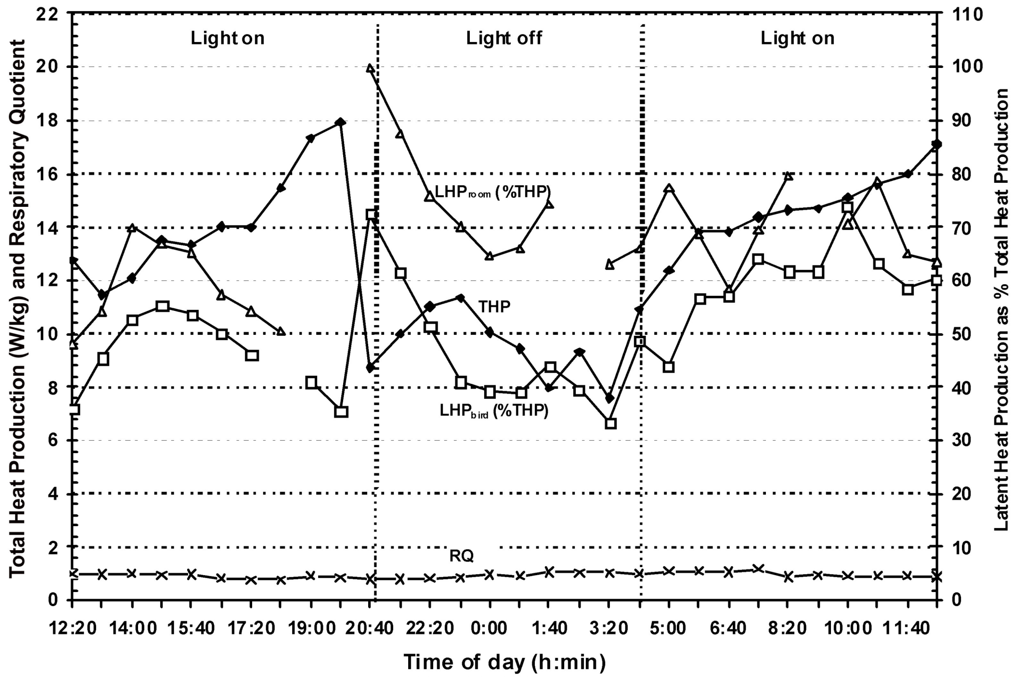

Figure 5 *Diurnal profiles of total heat production rate (THP), respiratory quotient (RQ), and latent heat production rate (LHP) as % THP for ad-lib fed four-day-old W-36 pullets under 31°C temperature. Birds had water from nipple drinkers. THP and RQ were averaged over four chambers while* $\mathrm{LHP_{bird}}$ *and* $\mathrm{LHP_{room}}$ *were each averaged over two chambers.*

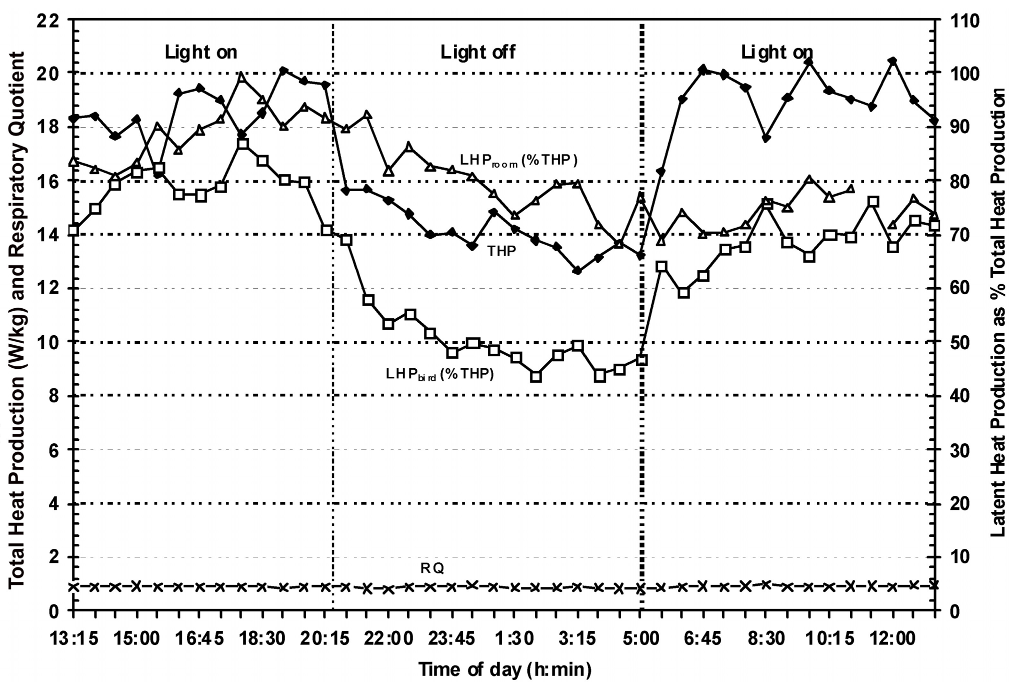

Figure 6 *Diurnal profiles of total heat production rate (THP), respiratory quotient (RQ), and latent heat production (LHP) as % THP for ad-lib fed four-day-old W-98 pullets under 31°C temperature. Birds had water from nipple drinkers. THP and RQ were averaged over four chambers while* $\mathrm{LHP_{bird}}$ *and* $\mathrm{LHP_{room}}$ *were each averaged over two chambers.*

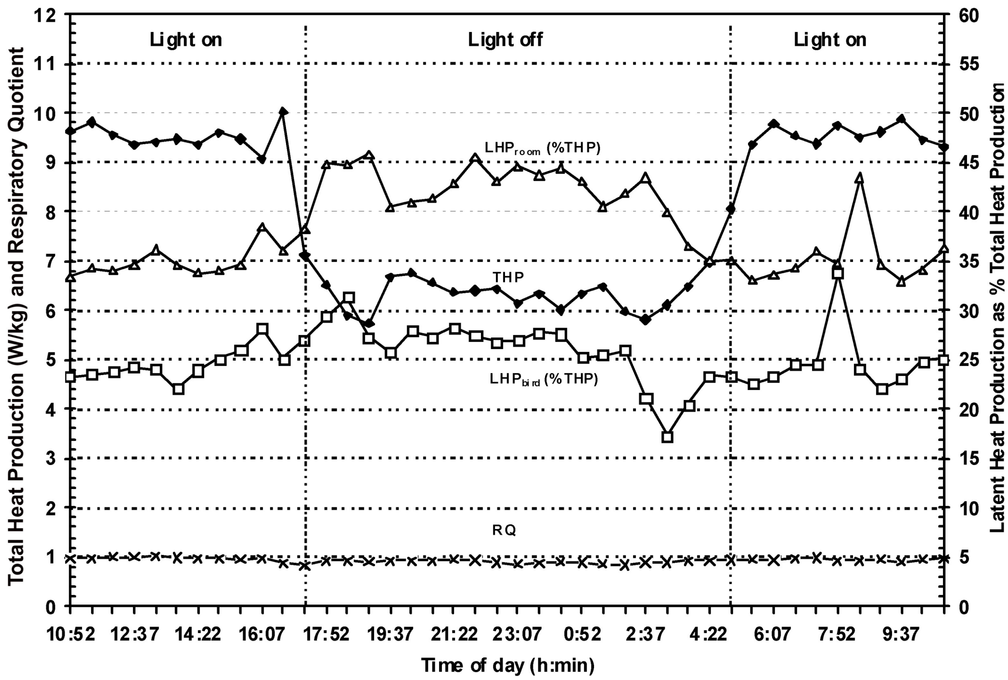

Figure 7 *Diurnal profiles of total heat production rate (THP), respiratory quotient (RQ), and latent heat production (LHP) as % THP for ad-lib fed 10-week-old W-36 layers under 24°C temperature. Birds had water from nipple drinkers. THP and RQ were averaged over four chambers while* LHP_{bird} *and* LHP_{room} *were each averaged over two chambers.*

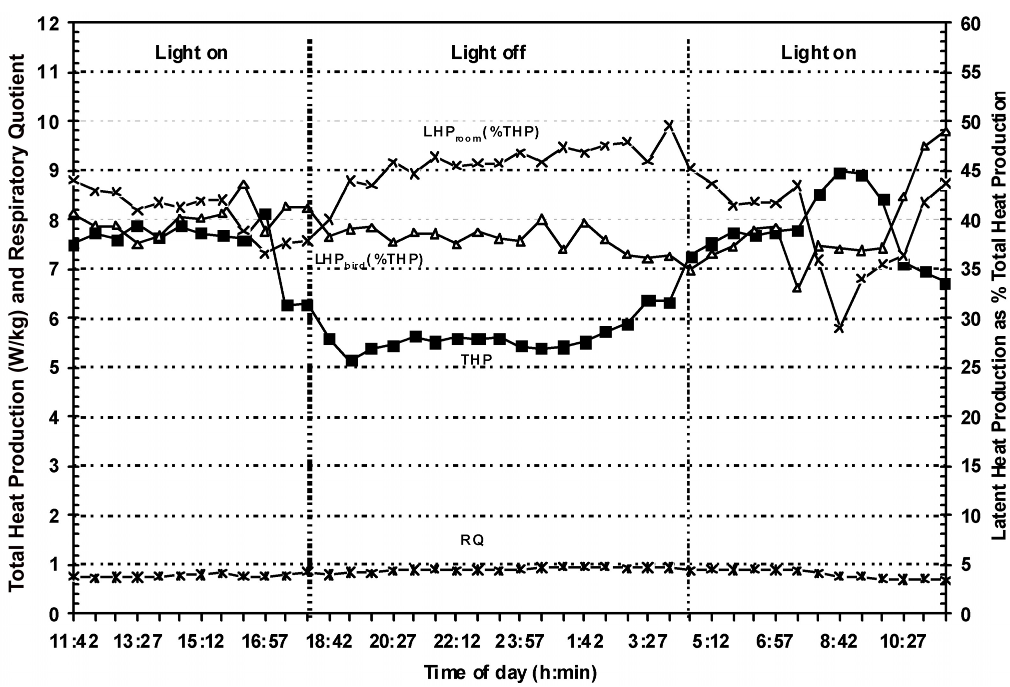

Figure 8 *Diurnal profiles of total heat production rate (THP), respiratory quotient (RQ), and latent heat production (LHP) as % THP for ad-lib fed 21-week-old W-36 layers under 24°C temperature. Birds had water from nipple drinkers. THP and RQ were averaged over four chambers while* LHP_{bird} *and* LHP_{room} *were each averaged over two chambers.*

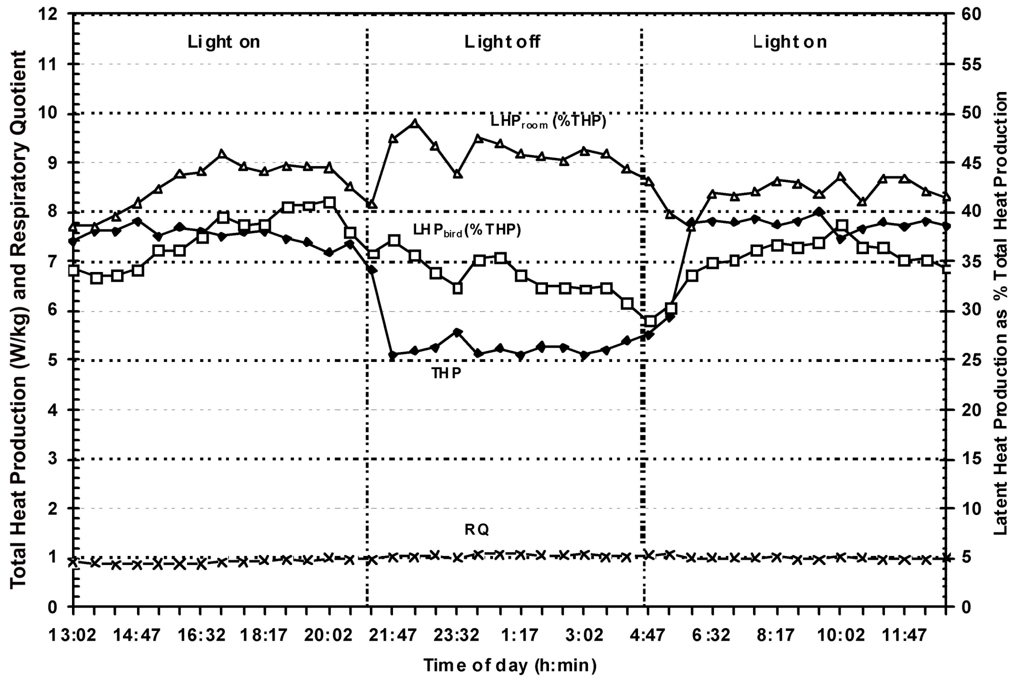

Figure 9 *Diurnal profiles of total heat production rate (THP), respiratory quotient (RQ), and latent heat production (LHP) as % THP for ad-lib fed 37-week-old W-36 layers under 24°C temperature. Birds had water from nipple drinkers. THP and RQ were averaged over four chambers while* LHP_{bird} *and* LHP_{room} *were each averaged over two chambers.*

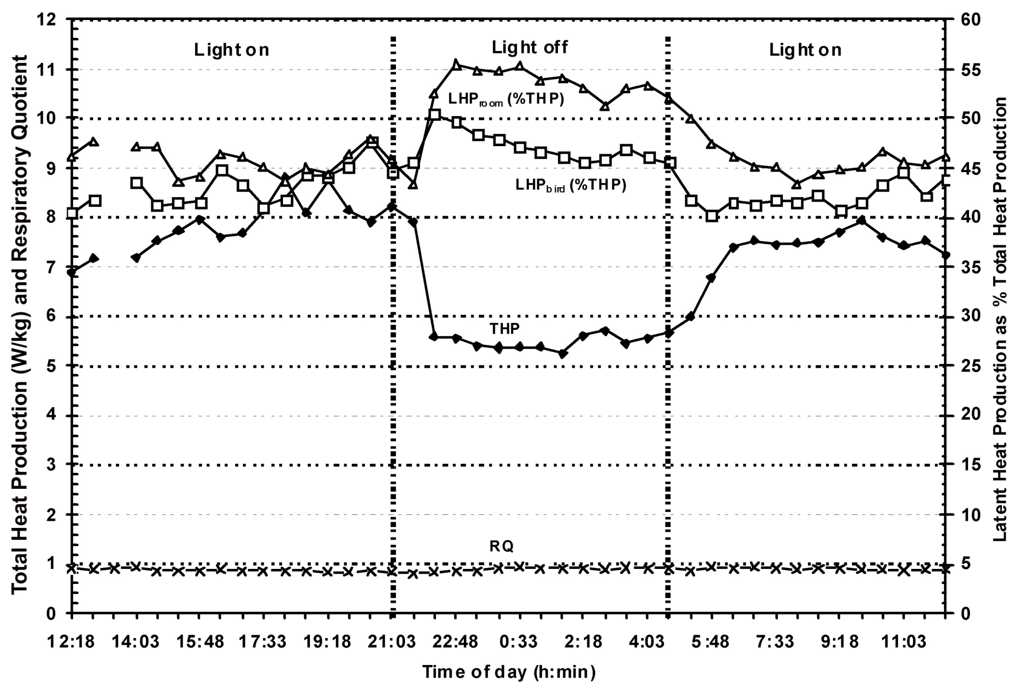

Figure 10 *Diurnal profiles of total heat production rate (THP), respiratory quotient (RQ), and latent heat production (LHP) as % THP for ad-lib fed 64-week-old W-36 layers under 24°C temperature. Birds had water from nipple drinkers. THP and RQ were averaged over four chambers while* LHP_{bird} *and* LHP_{room} *were each averaged over two chambers.*

was presumably a result of intense physical activities and/or quick evaporation of external moisture source. For laying hens at 21 to 64 weeks of age, LHP_{bird} was 29% to 50% (averaging 39%) THP and LHP_{room} was 29% to 55% (averaging 45%) of THP. The higher specific HP of the pullets could have resulted from their developmental growth and larger surface to volume ratio.

CONCLUSIONS

Heat and moisture production rates (HP and MP) of modern pullets (W-36 and W-98 strains) and laying hens (W-36 strain) were measured under conditions that represent commercial production settings using large indirect calorimeters. Latent HP (LHP) and sensible HP (SHP) were expressed as bird or room level. The following conclusions were drawn.

- Total HP (THP) of modern pullets was 12% to 37% higher than that of pullets 20-50 years ago. THP of modern W-36 laying hens was 12% higher than that predicted by CIGR (1999) model at the onset of egg production, and the difference became negligible with time.
- The W-98 pullet showed higher THP than the W-36 counterpart. W-98 and W-36 pullets reached their metabolic peak at about 10 and 14 days of age, respectively.
- Moisture evaporation from feces elevated room LHP by 8% to 38% (averaging 14%) during light period and by 21% to 79% (averaging 43%) during dark period. The resultant reduction of room SHP was 4% to 17% (averaging 11%) during light period and 14% to 33% (averaging 22%) during dark period.
- HP was significantly lower in darkness than in light period, 23% to 34% lower for THP.
- Percentage of THP as LHP varied from 17% to 87% (averaging 47%) at bird level and from 33% to 99% (averaging 62%) at room level for pullets. For layers, the percentage varied from 29% to 50% (averaging 39%) at bird level, and from 29% to 55% (averaging 45%) at room level.
- Respiratory quotient (RQ) averaged 0.94 for the experimental pullets and 0.91 for the laying hens.
- Regression models relating HP and bird body mass were developed.

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REFERENCES

ASHRAE. 2001. *ASHRAE Handbook—Fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Boshouwers, F.M.G., and E. Nicaise. 1985. Automatic gravimetric calorimeter with simultaneous recording of physical activity for poultry. *British Poultry Science* 26(4):531-541.

Brody, S. 1945. *Bioenergetics and Growth*. New York: Reinhold Publishing Corporation.

Chepete, H.J., and H. Xin. 2002. Heat and moisture production of poultry and their housing systems: Literature review. *ASHRAE Transactions* 108(2):448-466.

CIGR. 1999. *CIGR Handbook of Agricultural Engineering*. Animal Production & Aquacultural Engineering, Vol. 2. St. Joseph, Mich.: American Society of Agricultural Engineers.

Feddes, J.J.R., J.B. McQuitty, and P.C. Clark. 1985. Laying hen and moisture production under commercial conditions. *Canadian Agricultural Engineering* 27(1):21-29.

Gates, R.S., D.G. Overhults, and S.H. Zhang. 1996. Minimum ventilation for modern broiler facilities. *Transactions of the ASAE* 39(3):1135-1144.

Han, T., and H. Xin. 2000. Effects if intermittent lighting on breeder chicks provided with "in transit" nutrients. *Transactions of the ASAE* 43(6):1767-1770.

Havenstein, G.B., S.E. Scheidelar, P.R. Ferket, M.A. Qureshi, V. Christensen, and W.E. Donaldson. 1991. A comparison of the 1957 Athens/Canadian random bred control strain with the 1991 Arbor Acres broiler when fed diets typical of those fed in 1957 and 1991. In *Proc. North Carolina State Poultry Supervisors' Short Course, 1 April 1992.*

Hyline. 2000-2001. Hy-Line W-36 Commercial Management Guide. Hy-Line International, Dallas Center, Iowa, USA.

Ketelaars, E.H., A. Arets, W. van der Hel, A.J. Wilbrink, and M.W.A. Verstegen. 1985. Effect of housing system on the energy balance of laying hens. *Netherlands Journal of Agricultural Science* 33(1985):35-43.

Li, Y., T. Ito, and S. Yamamoto. 1991. Diurnal variation in heat production related to some physical activities in laying hens. *British Poultry Science* 32(4): 821-827.

Longhouse, A.D., H. Ota, and W. Ashby. 1960. Heat and moisture design data for poultry housing. *Agricultural Engineering* 41(9):567-576.

MacLeod, M.G., and T.R. Jewitt. 1984. Circadian variation in the heat production rate of the domestic fowl, gallus domesticus: Effects of limiting feeding to a single daily meal. *Comparative Biochemistry and Physiology* 78A(4):687-690.

May, J.D., and B.D. Lott. 1994. Effects of light and temperature on anticipatory feeding by broilers. *Poultry Science* 73(9):1398-1403.

O'Connor, J.M., J.B. McQuitty, and P.C. Clark. 1987. Heat and moisture loads in three commercial broiler breeder barns. *Canadian Agricultural Engineering* 30(2):267-271.

Ota, H., and E.H. McNally. 1961. Poultry respiration calorimetric studies of laying hens, Single Comb White Leghorns, Rhode Island Reds, and New Hampshire × Cornish Cross. Agricultural Research Service. U.S. Department of Agriculture.

Ouwerkerk, E.N.J. van, and S. Pedersen. 1994. Application of the carbon dioxide mass balance method to evaluate ventilation rates in livestock buildings. In *Proc. XII CIGR World Congress on Agricultural Engineering. August 29-September 1, Milano, Italy*, Vol. 1:516-529.

Reece, F.N., and B.D. Lott. 1982a. Heat and moisture production of broiler chickens during brooding. *Poultry Science* 61(3):661-666.

Reece, F.N., and B.D. Lott. 1982b. The effect of environmental temperature on sensible and latent heat production of broiler chickens. *Poultry Science* 61(8):1590-1593.

Riskowski, G.L., J.A. DeShazer, and F.B. Mather. 1977. Heat losses of White Leghorn laying hens as affected by intermittent lighting schedules. *Transactions of the ASAE* 20(4):727-731.

Xin, H., I.L. Berry, and G.T. Tabler. 1993. Feeding and drinking patterns of broilers subjected to different feeding and lighting programs. *Applied Poultry Research* 2(4):365-372.

Xin, H., H.J. Chepete, J. Shao, and J.L. Sell. 1998. Heat and moisture production and minimum ventilation requirements of Tom turkeys during brooding-growing period. *Transactions of the ASAE* 41(5):1489-1498.

Xin, H., and J.D. Harmon. 1996. Responses of group-housed neonatal chicks to post-hatch holding environment. *Transactions of the ASAE* 39(6): 2249-2254.

Xin, H., M.C. Puma, R.S. Gates, and D.U. Ahn. 2002. Effects of drinking water temperature on laying hens subjected to warm cyclic environments. *Poultry Science* 81:608-617.

Xin, H., J.L. Sell, and D.U. Ahn. 1996. Effects of light and darkness on heat and moisture production of broilers. *Transactions of the ASAE* 39(6):2255-2258.

Zulovich, J.M., H.B. Manbeck, and W.B. Roush. 1987. Whole-house heat and moisture production of young floor brooded layer pullets. *Transactions of the ASAE* 30(2):455-458.